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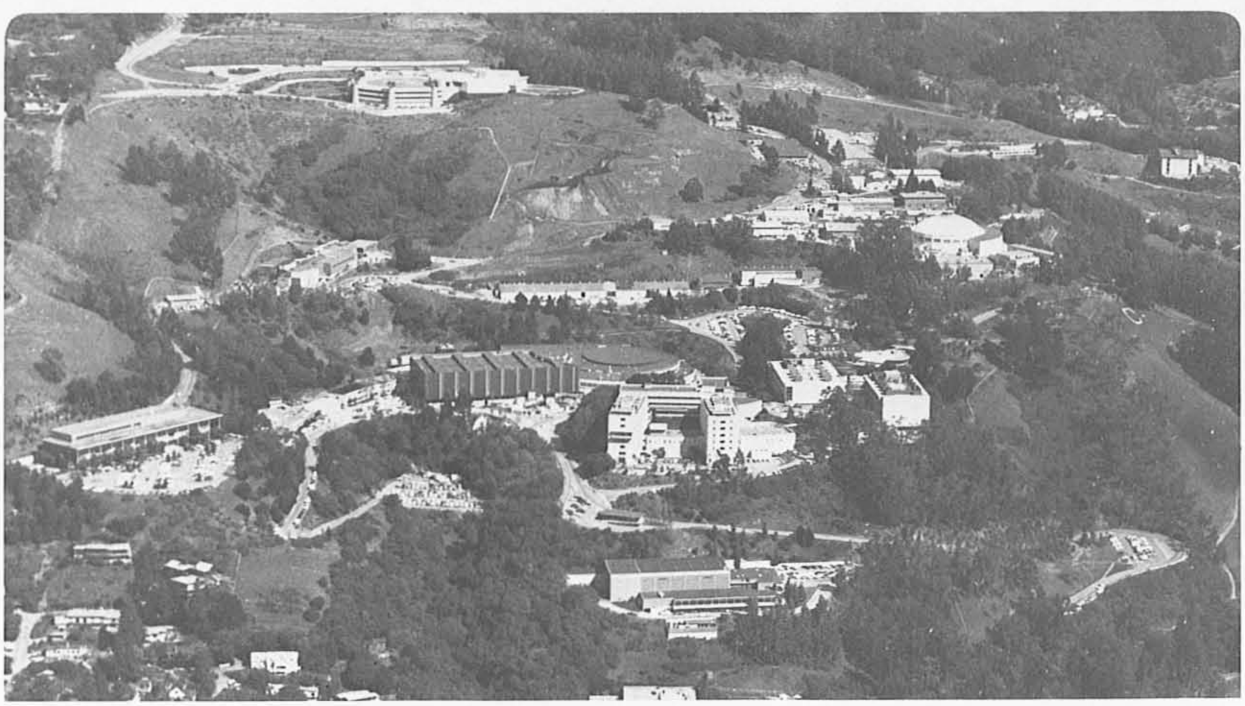

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AN ALTERNATE METHOD FOR DESIGNING DIPOLE MAGNET ENDS

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Abstract

Small bore superconducting dipole magnets, such as those for the SSC, often have problems in the ends. These problems can often be alleviated by spreading out the end windings so that the conductor sees less deformation. This paper presents a new procedure for designing dipole magnet ends which can be applied to magnets with either cylindrical or conical bulged ends to have integrated field multipoles which meet the constraints imposed by the SSC lattice. The method described here permits one to couple existing multiparameter optimization routines (i.e., MINUIT with suitable independent parameter constraints) with a computer code DIPEND, which describes the multiples, so that one can meet any reasonable objective (i.e., minimizing integrated sextupole and decapole). This paper will describe how the computer method was used to analyze the bulged conical ends for an SSC dipole.

Background

Small bore superconducting dipole and quadrupole magnets, such as those being developed for the SSC, often have fabrication problems. The study of various end configurations has resulted because of shorts and conductor motion which have been observed in a number of the SSC test magnets. At LBL, two types of ends which have smaller applied deformation are under active development. The ends under development include: (1) constant perimeter ends[1,2] which have a cylindrical outside surface which matches the dipole straight section[3] and (2) cut cone "flared" ends which permit large radii of curvature.[4] Several magnets using the "flared" end were built and tested at LBL during 1984 and 1985.[5]

Several methods for designing ends have been used. One extreme includes winding the end over a rigid form and forcing the conductor into a rigid shape even if the conductor doesn't wind that way. The other extreme is to wind the conductor loosely and let it assume the minimum strain position it wants to take. When the second approach is used, one has to mold the wedges and spacers to fit the shape the conductor naturally wants to assume.[6] The first extreme is often, but not always, easy to calculate magnetically. The second extreme is often difficult to do magnetic calculations on so this design method is often iterative (one builds, one measures, one modifies, one measures and so on).

Types of Ends which can be Calculated Using the DIPEND Program

Three general types of ends have been studied at LBL for superconducting dipole magnets. These include: ends which have cylindrical boundaries, ends which have simple conical boundaries and ends which have complex conical boundaries. The DIPEND program can calculate ends of each of three types.Within each category of end, the conductor can follow a variety of paths.

The cylindrical end is characterized as an end which has cylindrical boundaries. In general, these boundaries have radii which are the same as the two dimensional sections of the coil. A cylindrical end could have the two dimensional section collars extended over the end. (The iron could also be extended over the end.) The simple conical "flared" end is characterized by the circular shape the cone makes as it intersects a plane which is perpendicular to the axis of the magnet. The complex cone end (or cut cone, "flared", end) is characterized by the elliptical shape the cone (cones) make as they intersect a plane which is perpendicular to the axis of the magnet. Figure 1 illustrates three of the four types of end configurations that can be calculated with the DIPEND program--see Table 1.

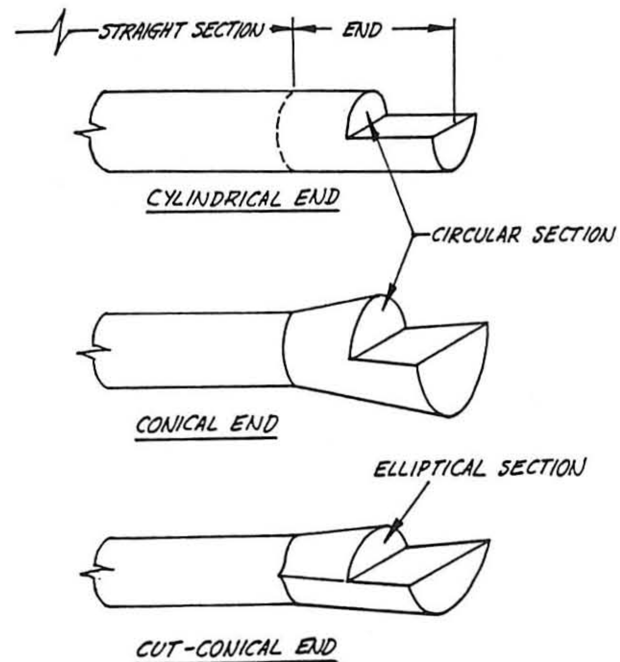

Figure 1. Examples of various dipole magnet end types (see Table 1)

Within each end type a couple of coil variations can be calculated. The first is the so called straight type of end where the superconductor is forced to be perpendicular to the cone or cylinder as it goes over the pole. The second variation is the natural constant perimeter end where the cable lays back on the surface of the cylinder or cone. This latter type is characterized by the fact that the length of the arc is the same for the outside and inside edge of the cable.

Any of the three types of ends can be built with the coils squeezed down toward the mid-plane before the conductor is allowed to go over the pole. This technique increases the average radius of the conductor as it goes over the pole and thus reduces the strain the conductor sees. The disadvantage of this approach (particularly in a cylindrical end) is that only the integrated sextupole is eliminated from the integrated field. The squeezed down end simplifies construction by reducing the number of spacers in the end region. In addition to squeezing down the end, one can also bunch the blocks of conductor together or keep them separated as they go over the pole. Figures 2 and 3 illustrate the concept of squeezed down and bunched ends.

Coil Geometry Calculations

This section describes coil block geometry calculations. We will describe a flared-end dipole as shown in Figure 4 (calculations for cylindrical end shapes are similar). Using the given straight section geometry (i.e., the SSC NC-9 cross section), the y-projection of the inner and outer edge

Table 1. Examples of dipole end geometry which can be calculated with Program DIPEND

	Cross-over Treatment				Ramp Treatment	
	Coil Placement		Conductor Path			
End Surface Shape	Separated (1)	Bunched	Constant Perimeter	Normal at Pole	With Squeeze Down (3)	With Outer Wedge at Z=Z1 (3)(4)
Cylindrical	x	x	x	x	(2)	(2)
Conical	x	x	x	x	x	x
Cut-conical	x	x	x	x	x	x
Hybrid (5)	x	(2)	x	(2)	(2)	(2)

(1) Z1 and Z2 specified for each coil.
(2) Option not applicable or currently available.
(3) "Bunched" coils only--not separated.
(4) Such that centerline of bunched and squeezed-down cross section @ Z = Z1 is normal to cone surface.
(5) Conical inner surface, cylindrical outer surface.

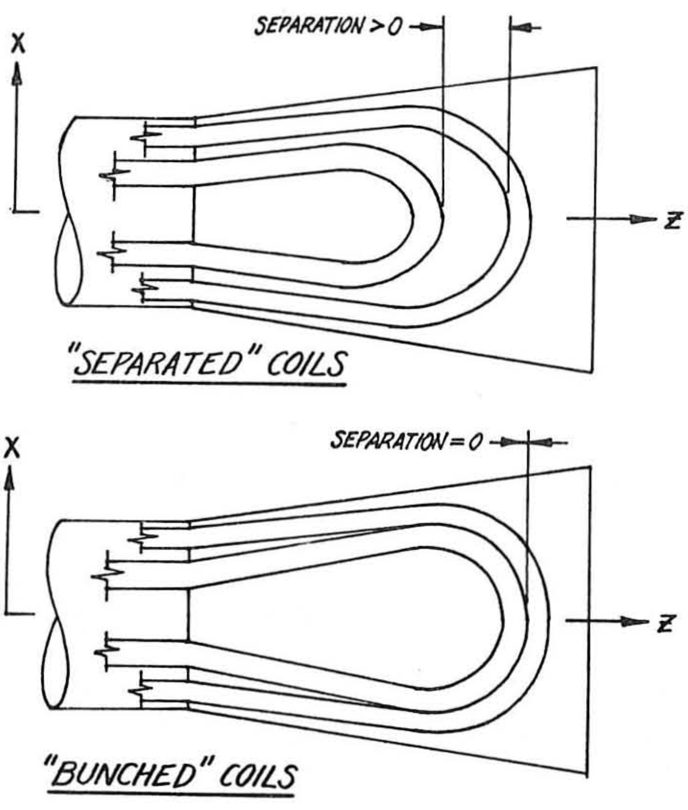

Figure 2. Examples of separated and bunched coils on a conical end (see Table 1)

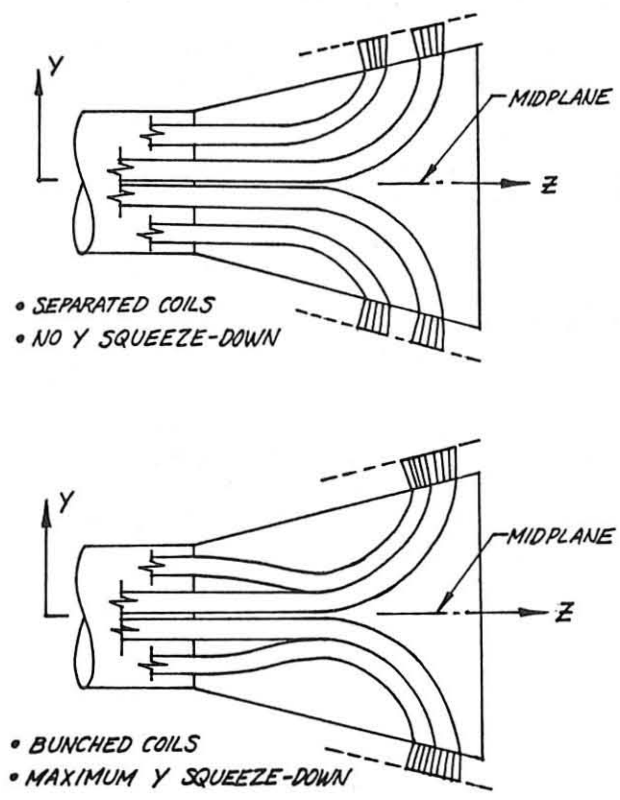

Figure 3. Examples of unsqueezed and squeezed down coils on a conical end (see Table 1)

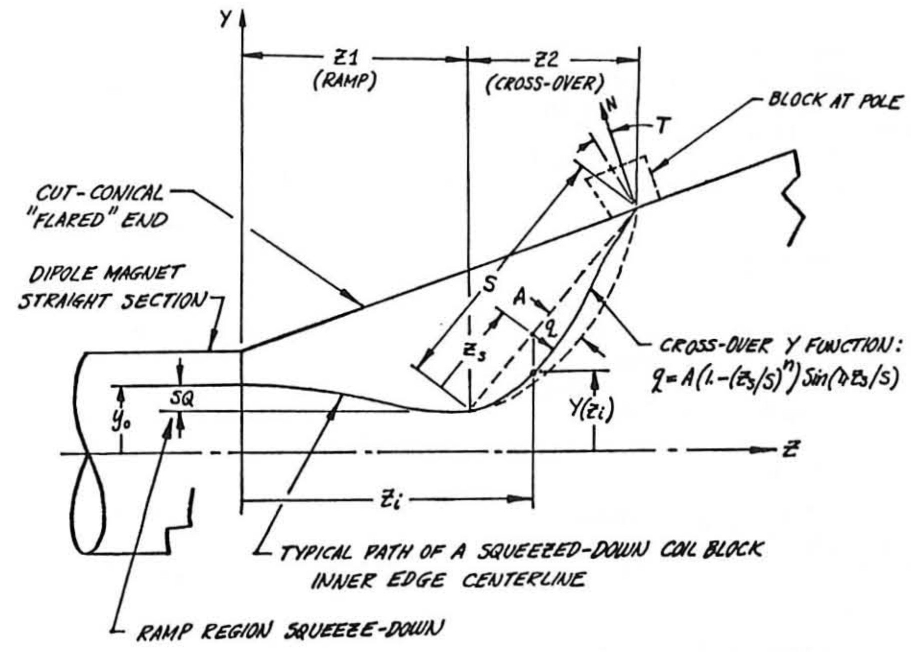

Figure 4. Schematic representation of the Y-Z projection of a squeezed down coil centerline path on a conical end

centerlines of each block is prescribed over the conical surfaces as functions of the given independent characteristic end parameters Z1 and Z2.

Figure 4 shows a typical *inner* edge path for a set of blocks which are to be squeezed down near the X-Z midplane in the "ramp" region prior to progressing over the pole in the "cross over" region. The squeeze down parameter, SQ, is either zero or a calculated function of the end geometry to provide a particular orientation of the group of blocks (up to 6) at the end of the ramp. The power term, n, in the cross over Y function is another independent parameter selected to modify the X-Z and Y-Z projections of the coil path as desired to: (1) fit the shape of a given magnet design, (2) influence the magnetic calculations, (3) reduce the conductor strain, or (4) reduce the gap between the outer edge of the coil and its outer conical surface by reducing coil twist.

Calculations of the coil block centerline *outer* edge path are similar except when a constant perimeter end design is specified. In this case, the pole tilt angle, T, (Figure 4) is varied in an iterative numerical integration loop until the outer edge centerline path length is equal to the inner edge path length.

The five coil geometry parameters, Z1, Z2, SQ, n and T along with the end cone angles are all independent, potentially optimizable, parameters which influence the magnetic performance of a dipole end.

Once the inner and outer edge paths of the coil block centerlines are calculated, the block corner positions are found using the number of block conductors, the conductor shape (typically a narrow, keystoned strip) and the block's pitch, yaw and twist from the centerline paths. The coil block X-Y cross section is closely approximated by a pair adjacent trapezoids which are functions of local geometry. The coil spacer block geometry--i.e., "shoes", islands ("teardrops") and wedges is finally calculated from coil block position information. In addition to tabulated geometry output and magnetic performance information, DIPEND provides useful two-dimensional plots of: (1) coil centerlines, (2) coil corners and (3) spacer block corners (see Figure 5).

Magnetic Field Analysis

The magnetic analysis consists of calculating the infinite integral of the field along the axis of the dipole. This integrated field is the field which really counts when one analyzes the physics of particle beams passing along the length of the dipole or quadrupole magnet. The integrated field from minus infinity to plus infinity is two dimensional. This integral can be expanded into multipoles just as the two dimensional field can (at the dipole center). The integrated field (from $-\infty$ to $+\infty$) can also be calculated for a dipole with a cylindrical iron shell with infinite permeability provided the iron shell also extends from $-\infty$ to $+\infty$).

The magnet end created by the DIPEND code is divided into a large number of short current segments. The integrated current in the direction of the magnet axis is used to calculate the infinite integrated field which is in turn expanded into multipoles. Since magnet ends calculated by DIPEND are generally symmetric, the integrated field is also symmetric. (A symmetric dipole end will develop only normal dipole, sextupole, decapole, 14 pole and so on. A symmetric quadrupole end will develop only normal quadrupole, 12 pole, 20 pole, 28 pole and so on.)

In the DIPEND program, conductor current in the two dimensional coil and the sections of end may be distributed in three ways for comparison. In one case the block current (the sum of the currents in all the conductors in that block) is put at center of the block. In the second case, the current is placed at the center of each conductor. In the third case, the conductor current is divided into a number of current points. (Figure 6 illustrates how the straight section coils are divided into discrete currents.) The two dimensional field and the integrated field multipoles thus calculated depend very much on how the coil current is subdivided. (The more the coil is subdivided the more accurate the two dimensional and integrated fields calculated will be.) The effect of the method of subdividing the current in a NC-9 magnet cross section with a conical end on the integrated field in the two dimensional section and the end is illustrated in Table 2.

Acknowledgments

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References

[1] H. Brechna, M.A. Green, "Pulsed Superconducting Magnets", Proceedings of the 1972 Applied Superconductivity Conference, May 1-3, 1972, Annapolis, MD.

[2] H. Fulton and J. Carson, "Fermi Lab Drawing SSC Dipole Magnet 1 m long 4 cm Bore Constant Perimeter Inner Saddle", Sept. 85.

[3] J. Royet, private communication on the LBL constant perimeter end to be reported later.

[4] S. Caspi, M. Helm, and L.J. Laslett, "A Flared End Design for the SSC Dipole", Internal LBL report LBID 1417, June 1988.

[5] C. Taylor et al., IEEE Transactions on Magnetics MAG-21, No. 2, p. 971 (1985).

[6] R. Perin, private communication on the LMC end design where the conductor forms a natural shape.

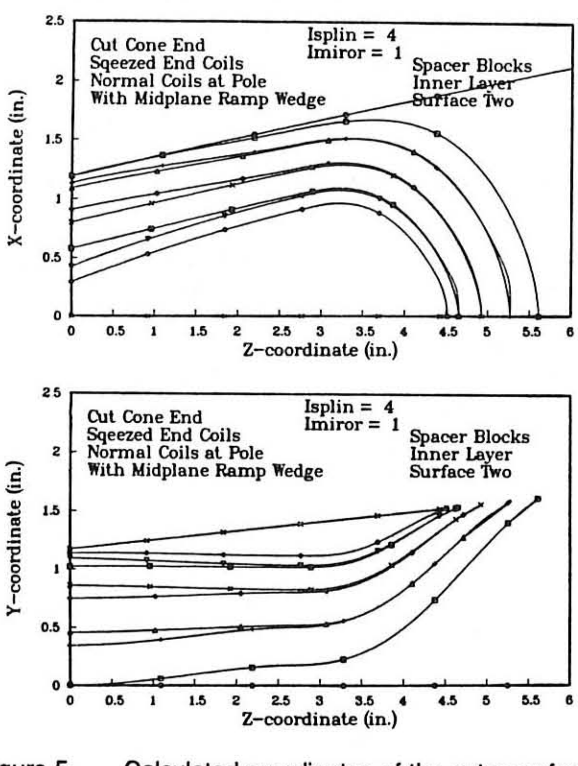

Figure 5. Calculated coordinates of the outer surface of coil spacers for a squeezed and bunched layer on a cut-conical end

Table 2. Integrated Field Multipoles.(1) A Comparison for 3 Different Current Distribution Assumptions (See Figure 6 for Coil 2D Cross section)

Multipole	Two Dimensional Coil Integrated B with Iron (Tm)	End Integrated B w/o Iron (Tm)
with a single current at Block Center(2)		
1	116.4462	0.5625
3	0.1230	-0.0001
5	-0.1008	-0.0010
7	-0.0076	0.0000
9	0.0007	0.0000
with current at the center of each turn		
1	115.4659	0.5666
3	0.0703	-0.0044
5	-0.0093	0.0000
7	0.0006	-0.0001
9	0.0001	0.0000
each turn divided into 6 radial steps		
1	116.2871	0.5707
3	-0.0067	-0.0045
5	-0.0105	0.0000
7	-0.0018	0.0000
9	-0.0007	0.0000

(1) At a radius of 10.0 mm.
(2) A poor approximation for large coil blocks.

TWO DIMENSIONAL NC-9 CROSS-SECTION

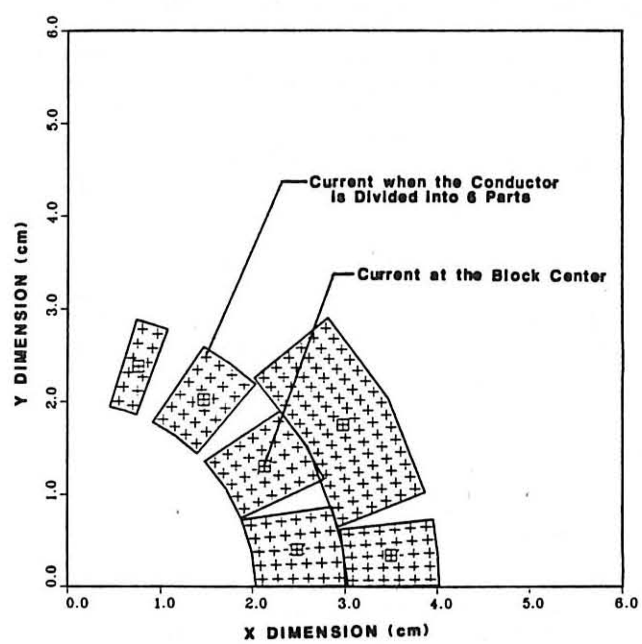

Figure 6. An example of dividing conductor blocks in the two dimensional quarter dipole coil cross section
Note: Crossed squares are currents at the block center, and crosses are currents where each conductor is divided into six parts (see Table 2)